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Seafood production in Northern Norway: Analyzing variation and co-development in aquaculture and coastal fisheries

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ABSTRACT

Norway is one of the leading ocean-based food production nations. Its seafood industry comprises wild-capture fisheries and farmed fish production. Both industries play a provisional role but also contribute to economic development of the country and help sustain coastal communities, particularly, in Northern Norway. Coastal fishery has been the staple industry in Northern Norway for centuries, while aquaculture complemented the seafood production in this region only approximately 40 years ago. To date, there has been limited knowledge on how the two industries co-developed in Northern Norway. While there are controversies regarding the potential cost and benefit of aquaculture to local communities, only a few studies have addressed co-existence of the two seafood industries in Northern Norway on a municipality scale. In this study, we compared the development of coastal fisheries and aquaculture in Northern Norway over a 14-year period (2005–2018) using a Bayesian approach that allowed to fit a model specific to each municipality, accounting also for temporal changes in both industries. A strong stochastic spatial variation characterized both industries, indicating a sizeable gap in the seafood production between the municipalities. Finally, the study showed that the fisheries and aquaculture likely did not affect each other's production, suggesting that there were no or few discernible conflicts or synergies between these two industries in Northern Norway. This study featured an advanced method for analyzing variation of seafood production per administrative unit that can be transferable to assess seafood development in other regions of Norway and beyond.

1. Introduction

In the 21st century, humans are increasingly relying on the ocean resources, particularly in the coastal regions, where sustainable growth of societies depends largely on maritime industries [1]. The increasing importance of the ocean and ocean resources for the coastal nations is emphasized in the Blue Economy initiative, where the utilization of ocean and coastal resources is a key for economic growth [2]. In the Blue Economy era, a larger part of economic development will be based on coastal and marine industries, including maritime transport, tourism, fisheries and aquaculture, and production of non-edible marine commodities such as drugs, cosmetics, and biofuel. Consequently, the Blue Economy is expected to create more jobs, as well as stimulate economy and demographic development of coastal communities [3].

Among the coast and ocean-based industries targeted by the Blue Economy, seafood production plays a particularly important role [4]. Globally, there is an increasing demand for food [5,6], but a growing agricultural harvest is impeded by the limited production areas and by the mounting environmental concerns over the high carbon footprint of meat and crops [7–9]. Moreover, future climate change is expected to have extensive negative effects on agriculture production [10,11]. Hence, in the context of food security, ocean-based food is a possible solution to meet future demands for sustenance [12–14], provided that the present climate change effects on marine ecosystems will not be

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detrimental [15].

Norway is one of the countries that contributes considerably to the world's seafood production. Seafood production is the second-largest export sector in Norway and is expected to play a significant role in the future, post-petroleum economy of Norway. Particularly, Norwegian cod, herring, and mackerel are the most important and high-quality seafood products both for national and international consumption. Norwegian aquaculture, on the other hand, is dominated by the salmonids production, 95% of which is directed for export.

Unlike aquaculture, the fisheries industry of Norway has a centuries-long history and bear a deep cultural meaning in the fisheries-dependent regions, especially, in Northern Norway. Aquaculture has complemented seafood production in Norway only in the recent decades (since 1970 s) and has supported the economic role of fisheries in the rural areas including Northern Norway [16]. However, it remains open to question how the two industries have co-existed in Northern Norway since the onset of fish farming. While seafood production statistics are usually analyzed on a national level, scientists and policy makers might be interested in detecting small-scale (municipality) factors that determined the success of each industry in the recent decades and in revealing the reciprocal effects of the two industries on a municipality scale.

Therefore, in the present paper we apply a novel hierarchical Bayesian approach to explore the development in coastal fisheries and aquaculture over 14 years to answer the following questions:

1) Which municipality-level factors are associated with increased or decreased growth in fisheries and aquaculture production in Northern Norway?
2) How does spatial and temporal variation in fisheries landings compares to the variation in aquaculture production?
3) Do the two industries influence each other's growth in Northern Norway?

2. Background

2.1. Aspects of the seafood production regulations in Norway

Historically, the Norwegian coastal fishery was an open-access industry, where nearly anyone could start fishing for food and profit. Major changes, however, have occurred since the 1960 s following collapses of major fish stocks such as herring (1960 s), capelin (1970 s) and cod (1990 s). The deterioration of these stocks prompted Norwegian Government to implement fisheries closures and regulations to reduce fisheries capacity. Besides the introduction of Total Allowable Catch quotas (TAC), these new regulations limited the number of vessels that were allowed to fish [17,18].

Following the implementation of TAC, the Norwegian Parliament initiated an economic optimization of the fishing industry. The optimization commenced in the 1980 s with the introduction of an Individual Vessel Quotas (IVQ) system. The IVQ restricted access to fisheries only to a limited number of fishermen that met the qualification criteria [19,20]. Initially, the IVQ did not allow to transfer or trade quotas among vessels but with the subsequent modifications, the system became increasingly transferable, such that multiple quotas could be transferred to a single vessel [20].

This new regime of TAC and individual transferable and tradeable quotas (ITQs) had a range of implications on the society. First and foremost, the fishery has become a profitable and economically viable industry [21]. In addition, overfishing has decreased, and the industry has become more biologically sustainable [22]. However, as a result of quota transferability, the number of small-scale fishing vessels decreased [23], and quotas were mainly accumulated on fewer vessels owners, also called "the privileged few" [20]. Consequently, the number of active fishers has declined considerably [21]. Moreover, the few vessels that remained in the industry delivered fish to a few, selected number of locations, creating a severe geographical imbalance in the access to raw fish resources for processing [17]. As a result, several fish processing plants along the coast turned redundant and shutdown, particularly, in Northern Norway [17,24].

Although the fisheries reforms have improved the environmental and economic sustainability of the industry, resource privatization and introduction of market mechanisms inflicted negative externalities on the coastal communities [25,26]. First, the reforms were followed by a reduction in the number of fish processing plants and a concentration of the ownership of vessels and quotas, resulting in a reduction in the traditional fishing activity in many communities [26]. Second, the modernization and specialization of the fleet has also gradually decoupled the remaining industry from the local communities [27–29] and hence eroded local institutions and resilience [25,30,31].

However, new opportunities for social and economic development were brought by salmonids aquaculture [16]. In Northern Norway, the first official records of aquaculture production began in 1976 when about 300 tons of farmed fish were sold. Already in 2005, Northern Norwegian counties (i.e., the three Northernmost counties, Nordland, Troms and Finnmark) produced about 210 thousand tons of farmed fish, primarily, salmon (Statistics Norway).

Despite the potential beneficial effects of aquaculture on local communities, the Norwegian Government wanted to limit and control the growth of the aquaculture industry fearing that uncontrolled proliferation could lead to low market prices of the farmed fish and shortage of smolts. Therefore, The Government signed the first (preliminary) Aquaculture Act in 1973 but since then, the Aquaculture Act has been rewritten several times, with the latest edition released in 2005 (Lovdata LOV-2005–06–17–79).

By the Aquaculture Act, Norwegian Government and ministries are authorized to introduce regulations related to specific issues of fish farming in the country. One of the regulations defined by the Aquaculture Act is the issuing of fish farming licenses. In Norway, the issuing of aquaculture licenses is managed at several administrative and political levels. First, an aquaculture license consists of two different parts, a so-called company license to farm a specific species in a certain quantity, and a location license, which gives the right to farm a specific volume of fish at a single location. For salmonids farming, company licenses are issued by the Fisheries directorate of Norway, a state regulating institution. The location licenses are issued by the county, which is the regional administrative level between the state and the municipality level. The granting of a location license also requires permits from several state agencies with the power of veto (permits regarding pollution, food safety, fish health and diseases, sea navigation, and water resources). Further, the proposed location must also be in an area designated for aquaculture in the municipal area plan or must be granted an exception by the municipality. Finally, municipalities also coordinate the entire process and consider any secondary aspects of proposed aquaculture sites before they take the final decision [32].

Historically, the allocation of company licenses for farming of salmonids have been determined in allocation rounds (usually led by the municipality administration), based on the pre-determined criteria for each round [16]. The criteria in the different rounds have included, among others, the extent to which the proposed aquaculture activity is expected to support regional economic development, to control the spread of farmed fish diseases, to reduce escapees, and sustain the Saami ethnic minorities. For many rounds, it was also predetermined which regions or municipalities should get licenses [16]. Before 2002, licenses were issued for free, however from 2002 to 2013 a payment to the Norwegian Treasury (Statskassen) was demanded for all licenses, ranging from 2 mill. NOK to 10 mill. NOK. From 2013, new licenses were auctioned, manifesting the high value of aquaculture licenses [16,33].

With the development of salmonid fish farming in Norway and internationally, environmental consequences of fish farming became a highly debated topic among both researchers and practitioners [34–37]. In Norway, aquaculture received intense criticism from the environmentally concerned public due to its allegedly adverse environmental impacts that are hard to mitigate [38–40]. Among such factors are discharge of organic matter [41] and other pollutants from the production facilities [40], including the release of disease treatment and delousing compounds, harmful to crustaceans and other organisms [40, 42], and the reliance on other marine resources [40,43], to name some examples. Above all these effects that to a varying degree are common for aquaculture practices internationally [34], the Norwegian salmonid farming also poses a considerable danger for the fitness of the wild salmon populations [44].

There are multiple ways in which farmed salmonids may reduce population health of the wild counterparts. The salmon lice parasite that originates from salmon fish farms can afflict wild salmonids and cause mortality [40]. Next, escapees from the farms are another infamous complication of salmonids farming. Escapees interfere with the wild salmonid populations compromising their genetic stability, with the severity of these effects depending on the frequency of escapes, season, location, environmental conditions, and escapees' survival up to the spawning season of wild salmonids [45–47].

Consequently, over the years the environmental aspects of aquaculture production became a critical factor for the growth of this industry in Norway. In 2017, The Government released a new regulation of the Aquaculture Act, by which the coast of Norway was divided into the 13 aquaculture management areas. The responsible authorities assessed the environmental impact of aquaculture production sites in each of the 13 management areas, where this impact was mainly measured as the risk of salmon lice infestation of the wild salmonids. Based on the resultant risk category (low, mild or high lice infestation risk), the farms were allowed to increase production or were obliged to decrease production capacities. This procedure of allocating production licenses per management area was then designed to be repeated every 2 years (in 2019 and 2021), after the update of the environmental status assessment in each management area.

2.2. The interactions between aquaculture and wild capture fisheries in Norway

On a national scale, national and international regulations combined with the development of the seafood market are likely to impact the growth in seafood production from aquaculture and fisheries. For example, based on scientific advice, the annual Norwegian TACs are determined in international negotiations for the most important commercial stocks, and fish quotas are distributed among different vessel groups according to decisions made by the national co-management board [48].

For the Norwegian aquaculture, the national policy and regulations with respect to aquaculture licenses and taxation, as well as the international market for salmon, are important factors determining the growth of the industry. On a local scale, however, the growth in the salmon industry is limited by a plethora of factors including biophysical factors such as the presence of favorable aquaculture locations, but also by the priorities given by the municipalities' marine spatial planning processes [49]. In the future, the growth in fish farming may also be limited by the availability of competent labor, adequate infrastructure such as ports, roads, and salmon processing plants, but currently these are not the major factors. In addition, the presence of individuals with ample capital and entrepreneurial spirit for initiating salmon farming in different regions is also important for the development of the industry, and for the magnitude of local and regional economic impacts from it.

Historically, the fishing industry was mainly limited by the distance to the major fishing grounds, the distance to the market, and by favorable conditions for preservation of cod through drying. With more efficient transportation and preservation techniques (e.g. freezers), these limitations have been relaxed, and with the closing of the fisheries and the introduction of vessel quotas, the availability of capital for investment in quotas and vessels became consequential [17]. A relatively large portion of the national TAC is allocated to small coastal vessels (< 28 m length) [48]. In many communities, local ownership of vessels and quotas, good recruitment to the fishing profession, and the availability of port infrastructure and fish processing plants have secured a thriving local fishing industry [17]. These are probably the three essential factors that must be present, and negative local development in any one of them could provoke disparities among coastal communities with respect to wild capture fish production.

The rapid growth of the aquaculture industry is likely to interact with the local fishing industry in multiple ways [50]. First, aquaculture farms occupy marine space and could consequently inhibit near-shore fishing activities. Furthermore, the discharge of nutrients, excess feed and medications such as delousing agents to the environment could have negative impacts on coastal fish and shellfish populations [51]. These impacts are supposed to be mitigated through the marine spatial planning processes and regulations to prevent pollution. However, some negative impacts on coastal fish stocks and coastal fishing activity from a growing aquaculture industry could be expected in the long run.

Second, the fishing and aquaculture industries are likely to compete for labor. The current centralization with a movement of people from rural coastal communities to larger cities [52] is likely to exacerbate this competition and could, depending on the quality of the jobs in the two industries, inflict the growth in either fishery or aquaculture or both. Particularly, aquaculture industry provides a variety of occupations that require higher education, and it has been hailed as having a potential for attracting younger and highly educated people back to the peripheral regions, while fisheries alone is unlikely to sustain population growth in these regions [53,54].

Third, aquaculture and local fisheries depend on capital investments in salmon licenses and in vessel quotas, respectively, as well as on investments in specialized infrastructure for production, processing, and export [21,55]. With limited local capital available, the Norwegian aquaculture industry is to a large degree owned by international seafood companies [56,57], while the traditional coastal fishing industry in Norway is mostly owned by the local fishers and investors [58]. This difference makes it less probable that the two industries will compete for capital, however, in cases when both industries depend on a limited local capital, a negative interaction could be expected.

Finally, the fisheries and aquaculture industries can be seen as two different cultural dimensions. While the fishing industry has long traditions that are rooted in the coastal fishing and hunting culture, the aquaculture industry is more modern with roots in animal husbandry and agriculture [59]. These cultural differences might have been important for the establishment of aquaculture in the first place, making it unfavorable for aquaculture to evolve in traditional fishing strongholds.

While the focus is often on the numerous negative interactions between the two industries, we speculate that synergies could also be expected. Under an optimistic scenario, a growing aquaculture industry has a potential to secure small vulnerable communities by generating employment and tax revenues. In turn, a thriving community is also essential for the existence of a local fishing industry. In addition, the aquaculture industry in Norway could introduce new competences regarding fish processing and marketing, that could spill-over and eventually strengthen the fishing industry. Finally, partly because capture fisheries are highly seasonal, co-existing aquaculture and fisheries industries may benefit from each other through the sharing of infrastructure (e.g., ports, processing facilities) [60] and seasonal labor [61].

3. Methods

3.1. Study area

In this study, we focused on the 3 counties of Northern Norway (Nordland, Troms, and Finnmark) and their respective municipalities (Fig. 1). On the January 1st, 2020, a major administrative reform merged the Troms and Finnmark counties as well as several of the

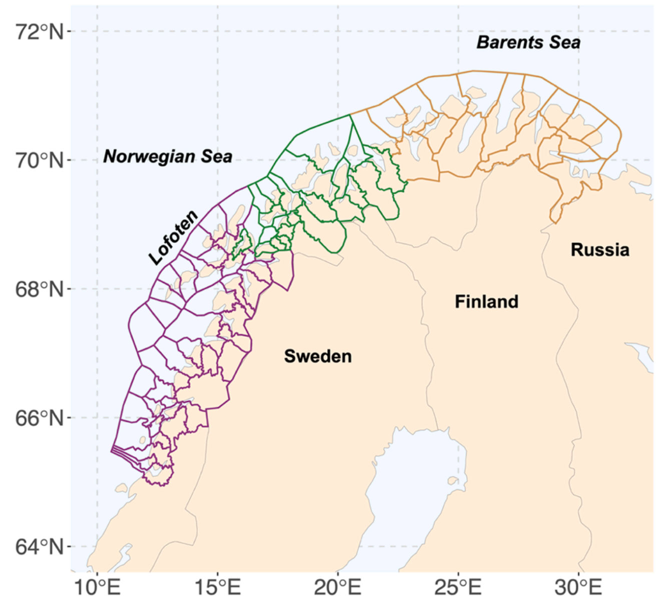

Fig. 1. Administrative borders between municipalities in Northern Norway. Color denotes the counties of Northern Norway as they were before 2019: purple – Nordland County; green – Troms County; brown – Finnmark county.

municipalities of these counties, but in the present analysis we used the geographic borders as they were before the reform.

A municipality is the smallest administrative unit in Norway. Focusing on municipalities rather than larger administrative areas allowed us to discern the differences in municipality-level factors that affected local seafood production. In addition, the smallest resolution of the fisheries landings data and of aquaculture annual yield data are both on a municipality level.

3.2. *Fisheries data*

To estimate annual wild-capture fisheries-based seafood production, we utilized the landings statistics by $<$ 28 m length vessels of the eight most economically important species of Northern Norwegian fisheries: Atlantic cod, capelin, haddock, Atlantic herring, saithe, Atlantic mackerel, and 2 crustacean species–deep water shrimp and red king crab. Although shrimps and red king crabs are caught only in some coastal municipalities, they have a high economic and social value for the coastal communities [62–64], thus we decided to include them in the study. There are other fish species that can be caught in the coastal waters of Northern Norway but most of them are less commonly used for human food and comprise a relatively small proportion of total landings (e.g., blue whiting, Greater argentine, Golden redfish). Therefore, these species were excluded from the analysis.

The landings statistics for the eight species for the years 2005–2018 were obtained from the Norwegian Directorate of Fisheries (www.fiskeridir.no). To calculate the total annual sea food production by fisheries, we summed the landings (tons) of the 8 species, per municipality. We note, however, that we relied only on the landings registered in each given municipality and reported to the Norwegian Directorate of Fisheries. We did not attempt to account for unregistered landings.

In cases where there was no data on how much fish landings were delivered to a municipality in a given year, we assumed that the fisheries production in this municipality and year was a true zero rather than missing fish landings record. In total, there were 123 such observations out of 1040 data inputs.

3.3. *Aquaculture data*

In Northern Norway, aquaculture is dominated by the production of salmon and rainbow trout. Although production of other species is currently under development, we only included salmonids aquaculture in the present analysis.

The estimation of total annual aquaculture production per municipality was based on the data provided by the Fisheries Directorate of Norway, covering the years 2005–2018. We used the following variables: annual amount of smolts seeded for production, monthly standing biomass of fish, annual harvest of produced fish, annual number of fish discarded at the slaughter plant, and annual number of fish moved from the production location or to the location.

The annual aquaculture yield per municipality (i) and year (j) was estimated as:

$$Y_{ij} = \Delta Biomass + Harvest + Removed \quad fish - Seeded \quad smolts \\ - Added \quad fish - Discard \tag{1}$$

Here, $\Delta Biomass$ is the difference of standing biomass of fish in December of the given year and December of the previous year; *Harvest* is the biomass of fish harvested in a given year (kg); *Removed* is the biomass of fish (kg) moved to another municipality due to excess of fish at a given location, disease outbreaks or other reasons (Cermaq Norway, Nova Sea AS, and Norway Royal Salmon, pers. com); *Seeded smolts* is the biomass of smolts (kg), seeded for production at the beginning of the production cycle; *Added fish* is the biomass of fish brought to the given municipality from another municipality, and *Discard* is the biomass of fish (kg) discarded at the slaughter plant.

In the data supplied by the Fisheries Directorate of Norway, *Seeded smolts*, *Discarded fish*, and *Added fish* variables were provided as counts of individual fish. To estimate the biomass of smolts, we assumed that the weight of each smolt was equal to 100 g. The biomass of discarded fish was calculated by multiplying the amount of discarded fish by 5, as the average weight of salmon and trout at the end of the production cycle is about 5 kg [65]. Finally, for the biomass of added fish we assumed that each fish weighted 1.5 kg. Although the weight of fish moved to the production site may vary from 0.5 kg to 2–3 kg, many are moved at the weight of about 1.5 kg (Cermaq Norway, Nova Sea AS, and Norway Royal Salmon, pers. com).

Since aquaculture production per year was calculated based on several assumptions (e.g., weight of moved fish, weight of smolts), inconsistencies occurred, such as negative total production. Out of 1040 observations, there were 25 with aquaculture production lower than 0. Negative total production values are not possible, if annual change in fish biomass is correctly adjusted for fish loss and added fish, so we attributed these values to flaws in the reported fish biomass data. We replaced such values with NA and did not include them in the analysis.

To clarify the terminology of the present study, the total fisheries landings per municipality is also referred to as "fisheries production" when compared with the annual total yield of aquaculture, which is referred to as "aquaculture production."

3.4. *Municipality statistics*

We included several municipality statistics that can be relevant to seafood production in the municipalities. The considered variables were municipality's sea area, its distance to the southernmost point along the Norwegian coast, municipality's population, population growth, number of unemployed, and percent of the population between 15 and 75 years old that are employed. The sea area of each municipality was obtained from the Norwegian Map Administration (Kartverket.no). The municipalities' population data, population growth, number of unemployed, were all accessed from Statistics Norway website (www.SSB.no). For the population growth per municipality data, we selected only the data points recorded in the first quarter of the year. Similarly, for the number of unemployed, where records are monthly, we selected only the January records. If no records on the number of unemployed were made in January, we used the data from the closest following month (e.g., March). In some instances, the number of unemployed was registered only once during a year—in November. Then those values were used in an annual unemployment covariate. In addition, aquaculture production was used as a covariate of fisheries production, and fisheries production as a covariate of aquaculture production. The histograms of all initially considered variables can be found in the Supplementary material (S3 Figure).

During exploratory analyses we discovered that unemployment rate and population of each municipality had a high variance inflation factor (VIF). When population and unemployment covariates were removed, all the remaining covariates had a satisfying VIF of below 3, indicating low levels of collinearity [66]. The remaining covariates were standardized to zero mean and a standard deviation of 1 prior to the analyses.

The data on municipalities' statistics had minor incompleteness issues. The number of unemployed had 37 missing observations; population and population growth both had 8 missing values, both for Harstad municipality (municipality number 1903) in 2005–2012. In addition, 7 missing data points in the percent in workforce variable were missing for Harstad municipality in 2005–2011. No missing value imputation techniques were applied, and the records with NA were omitted from further analyses.

For the joint analysis of fisheries and aquaculture data, we restricted both data series to municipalities that had at least 10 years of records. We note also that although 81 municipalities were of interest for the study (Fig. 1), the analysis included only 75 of them: 6 municipalities were excluded because they had less than 10 years of recorded observations, which was insufficient for temporal models. The excluded municipalities and their respective numbers were: Evenes (1853), Tjeldsund (1852), Målselv (1924), Sørreisa (1925), Storfjord (1939), and Tana (2025).

3.5. Bayesian random effects models

To investigate how the production of fisheries and aquaculture varied over time in relation to socio-economic factors and to each other's production rates, we applied a Bayesian model that included fixed and random effects. The models and their parameters are described in detail below.

Random-effects models are commonly applied to clustered, or repeated measurements, type of data [67]. In our study, observations of seafood production were recorded repeatedly from the same municipalities, and we can expect that records of seafood production within the same municipality are more correlated than between the municipalities. To account for a correlated structure of the data within a municipality, we considered municipality as a random effect in the models. In addition, we assumed a possible spatial (between the neighbor municipalities) and temporal (between the consecutive years) dependency in our data; therefore, we applied spatial-temporal mixed-effects models.

A popular class of models for spatially correlated areal (lattice) data is Intrinsic Conditional Autoregressive correlation models (ICAR) [68]. These models can be used to specify the distribution of the spatially correlated random effects, such as the municipality effect in the present study. An important feature of ICAR models is that a spatial random effect $u_i|u_{j\neq i}$ has a conditional normal distribution, with mean equal to the average of the mean effects of neighbors, and variance equal to the ratio of the overall spatial effect variance σ_u^2 and the number of neighbors [69]. Hence, a municipality with many neighbors will have lower variance than municipalities with fewer neighbors. Municipalities were considered as neighbors if they share one or several boundary points, which were defined by *poly2nb* function of the `spdep` package in R [70]. The plot of neighbors can be found in the Supplementary material (S4 Figure).

Within the class of ICAR models, three types of models can be applied to the areal data of our study: the Besag model, the Besag-York-Mollié (BYM) model, and the BYM2 model [71]. The difference between the three types of models lies in the formulation of the random effect: Besag model includes a structured correlated random component u_i, while BYM model decomposes spatial effect into a spatially correlated u_i and an unstructured, independent, and identically distributed random component (iid) v_i. The BYM2 model is a reparameterized version of BYM that includes a scaled spatially structured and an unstructured random effect and the mixing parameter ϕ [72,73]. In the BYM2, the mixing parameter measures the proportion of marginal variance attributed to structured and unstructured random components. In this study, we opted for the BYM2 model which has better interpretability of the spatial random effects (eliminates confounding between u_i, and v_i) [74]. In addition, BYM2 model is well suited for application of so-called penalized complexity priors for the precision of spatial random effects (model hyperparameters), and these priors are likely to provide a better fit by choosing less complex models as long as data complies with such choice [75].

To account also for the possible temporal correlation, we considered several models that included temporal components. The first model contained a general temporal trend (γ_j) which was a random walk of order 2 (RW2) function [76] and an unstructured temporal component ϕ_j (not to be confused with the mixing parameter ϕ in BYM2 model). In the next two candidate models, we assumed that the temporal trend consists of only a structured component γ_j of either RW2 type or a simple linear trend type. The 5th model incorporated two temporal components, ϕ_j and γ_j, but also included interaction between the spatial v_i and temporal ϕ_j. This is type I spatial-temporal interaction [77], which models an unobserved covariate that drives additional variation in the response variable, but this variation is not structured in space or time. Finally, we applied the Bernardinelli interaction model, which is simpler than the interaction type I model but has stricter assumptions. In this spatial-temporal model, there is a strictly linear overall temporal trend βt, and each municipality is allowed to deviate from this trend by δ_i. In other words, δ_i is a difference between the municipality's trend and overall trend, thus, is a type of spatial-temporal interaction. Since the final trend can be represented as $t(\beta+\delta_i)$, δ_i value lower than 0 suggests a less steep trend in a municipality than an overall positive trend, while a positive δ_i indicates steeper trend [78]. For the global negative trend, interpretation of δ_i is reversed. A more detailed mathematical definition of the models can be found in the Supplementary materials, section Bayesian spatial-temporal models.

In the models, we assumed Tweedie observational distribution of the data (called likelihood in the Bayesian terminology). Tweedie is a class of exponential distributions, where the variance and the mean are related through the power parameter [79]. The power value of 0, 1, and 2 generates well-known distributions—Normal, Poisson and Gamma, respectively [80]. For the power parameter between 1 and 2, Tweedie forms a mixture distribution, called a compound Poisson or compound Gamma distribution. In the compound Poisson Tweedie distribution, the total number of observations Y (in our case, the total number of fisheries landings or aquaculture yields) is a random Poisson variable, while a single observation X_i is a variable generated from a Gamma distribution, thus a strictly positive value (Eq. (8)) [81].

$$Y = \sum_{i=1}^{N} X_i \tag{8}$$

The advantage of the compound Poisson Tweedie distribution is that both exact zeros and positive value observations can be incorporated [82]. Therefore, this distribution is relevant for fisheries data, such as CPUE or catch weight [82,83] and appear to perform well in quantitative fisheries studies [84].

Next step in a Bayesian model construction is the selection of priors. We used default priors for power and dispersion parameters of the

Table 1

The simplified formulation of candidate random-effects models for fisheries production. $Log(FI_{ij})$ denotes the log-fisheries landings in a municipality i and year j; β_0 is the intercept, AR_{ij} is the area (km^2) of a municipality; WF_{ij} is the percent of people between 15 and 75 years old that were in the workforce; DI_{ij} is the ranked distance of a municipality from a southernmost point of Norway along the coast; AP_{ij} is the aquaculture production in a municipality i and year j; β_1 through β_5 are linear effects of the five covariates; u_i is the correlated (structured) spatial random effect; v_i is the unstructured spatial effect; γ_j is the temporal trend of type RW2 or linear; ϕ_j is the unstructured temporal effect; σ_{ij} is the spatial-temporal interaction of Type I; YR is a year of observation; β_6 is the overall linear temporal trend of the Bernardinelli model, and δ_i is a municipality-specific differential trend of the Bernardinelli model. For aquaculture data, the candidate models were the same, except that the response was aquaculture production in a municipality i and year j, and fisheries production was an additional covariate.

Model type	Formulation	
Spatial random-effects model	$Log(FI_{ij}) = \beta_0 + \beta_1 AR_{ij} + \beta_2 WF_{ij} + \beta_3 DI_{ij} + \beta_4 PG_{ij} + \beta_5 AP_{ij} + u_i + v_i$	(2)
Spatial-temporal model: no interaction, with temporal RW2 and random temporal effect	$Log(FI_{ij}) = \beta_0 + \beta_1 AR_{ij} + \beta_2 WF_{ij} + \beta_3 DI_{ij} + \beta_4 PG_{ij} + \beta_5 AP_{ij} + u_i + v_i + \gamma_j^{RW2} + \phi_j$	(3)
Spatial-temporal model: no interaction, with temporal RW2	$Log(FI_{ij}) = \beta_0 + \beta_1 WF_{ij} + \beta_2 DI_{ij} + \beta_3 GR_{ij} + \beta_4 UN_{ij} + \beta_5 AP_{ij} + u_i + v_i + \gamma_j^{RW2}$	(4)
Spatial-temporal model: no interaction, with linear temporal trend	$Log(FI_{ij}) = \beta_0 + \beta_1 WF_{ij} + \beta_2 DI_{ij} + \beta_3 GR_{ij} + \beta_4 UN_{ij} + \beta_5 AP_{ij} + u_i + v_i + \gamma_j^{Linear}$	(5)
Spatial-temporal interaction type I	$Log(FI_{ij}) = \beta_0 + \beta_1 AR_{ij} + \beta_2 WF_{ij} + \beta_3 DI_{ij} + \beta_4 PG_{ij} + \beta_5 AP_{ij} + u_i + v_i + \gamma_j^{RW2} + \phi_j + \sigma_{ij}$	(6)
Bernardinelli model	$Log(FI_{ij}) = \beta_0 + \beta_1 WF_{ij} + \beta_2 DI_{ij} + \beta_3 GR_{ij} + \beta_4 UN_{ij} + \beta_5 AP_{ij} + u_i + v_i + YR(\beta_6 + \delta_i)$	(7)

Tweedie distribution: normal prior with zero mean and variance of 10, and log gamma prior with shape and scale parameters 1 and 0.1, respectively. For using Tweedie likelihood in the models, we also divided the fisheries landings and aquiculture production by 1000, because Tweedie likelihood performs better on smaller-values data.

For all the fixed effects of the covariates (the slopes) we used weakly informative normal priors with zero mean and variance of 1. For the intercept, we adjusted the normal prior to have a mean of 0.0001 and variance of 2 (precision of 0.5).

The spatial random effect of BYM2 had two hyper-parameters—precision and mixing parameter ϕ.We assigned penalized complexity (PC) priors for both parameters. PC priors for precision τ_b and mixing parameter ϕwere defined as shown in the Eqs. (9) and (10), respectively.

$$P\left(\frac{1}{(\sqrt{\tau_b}} > 2\right) = 0.01 \tag{9}$$

$$P(\phi < 0.5) = 0.5 \tag{10}$$

The priors were chosen based on the recommendations and commonly used values [71,75]. Next, since PC prior is suitable also for the other model components, such as dynamic non-parametric temporal trends of RW2 type, we applied PC prior for RW2 temporal trend with parameters 1 and 0.01.

All the Bayesian models were fitted using the method of Integrated Nested Laplace approximation (INLA) [85,86], applied in R programming environment using the `INLA` package (version 22.05.07, May 2022) [87]. Unlike more conventional Markov Chain Monte Carlo (MCMC) sampling techniques often used for Bayesian models, INLA does not require computationally expensive sampling algorithms to estimate the posterior means of the model parameters (e.g., regression slopes and residual variance). Instead, INLA relies on numerical approximations to obtain the posterior distributions of model parameters, facilitating fast yet accurate estimation of parameters [78,88].

The considered models for fisheries were formulated as shown in the Table 1. For aquaculture, same models were used but the additional covariate was fisheries production. Note that Tweedie distribution assumes log-link function, therefore a logarithm of response variables is taken in the model formulas. Selection of the best fitting model among the candidate models was done using a diagnostic measure that is designed for a Bayesian analysis, the Deviance information criterion (DIC) [89]. The DIC compares models both in terms of fit and the complexity (number of parameters), and the model with the comparatively lowest DIC can be interpreted as best. For the details on how spatial-temporal model were coded in R for this study, we refer to the GitHub repository (https://github.com/marinaesp/spfood).

4. Results

4.1. Spatial and temporal variation in fisheries and aquaculture production

Our study included 14 years of observations (2005–2018), but for simplicity of illustrating comparisons we presented fisheries and aquaculture production in years 2005 and 2018 to highlight both the geographical and temporal differences in the two industries (Fig. 2 and Fig. 3). The variation in fisheries landings and aquaculture production over the whole range of years is shown in Supplementary figures (S1 Figure and S2 Figure).

There were noticeable differences in the fish landings between the municipalities within 2005 and 2018 but less dramatic differences were found between the two years (Fig. 2). First, we observed that both in 2005 and in 2018, there were a few municipalities that had the highest amounts of delivered fish. In 2005, such municipalities were Bodø (1804), Værøy (1957), Vågan (1865), Berg (1929), and Tromsø (1902). In 2018, leaders in coastal fisheries landings were again Vågan, Øksnes (1868), Tromsø and Masøy (2018) municipalities. However, in 2005 the maximal registered landings were higher (up to 40 thousand ton) than in 2018 (i.e., $\leq$ 32 thousand tons). Most of the municipalities in Northern Norway in both years delivered lower amount of fish (about$\leq$ 0–16 thousand ton).

In contrast to fisheries, aquaculture production increased considerably in 2018 compared to 2005 (Fig. 3). In 2005, the maximal aquaculture yield, registered in Alta (2012), was about 18 thousand tons. However, in 2018 Alta and Rødøy municipalities produced over 24 thousand tons of farmed fish. Aquaculture yield noticeably increased in 2018 also for many other municipalities in Northern Norway. For example, in municipalities Tromsø and Karlsøy (1936) in Troms County, Meløy (1837), Herøy (1818), Tysfjord (1850) municipalities of Nordland County, and Hammerfest (2004) and Kvalsund (2017) in Finnmark.

4.2. Bayesian random effects models

According to DIC of the fisheries models, the spatial-only model and the models that also included temporal effect without interaction were less optimal than the spatial-temporal interaction models, where lower DIC indicates better fit (Table 2). The DIC value for interaction type 1 model (32) was larger than DIC of Berardinelli model (17). Also, the Berardinelli model is more parsimonious than interaction type 1: there are 75 interaction terms estimated in the Bernardinelli model versus 1040 space-time interaction terms of the interaction type 1 model. Therefore, we preferred the Bernardinelli model as the final model for fisheries data. For the aquaculture production data, similar models were tested, and the Bernardinellli model was also chosen as the best (Table 3).

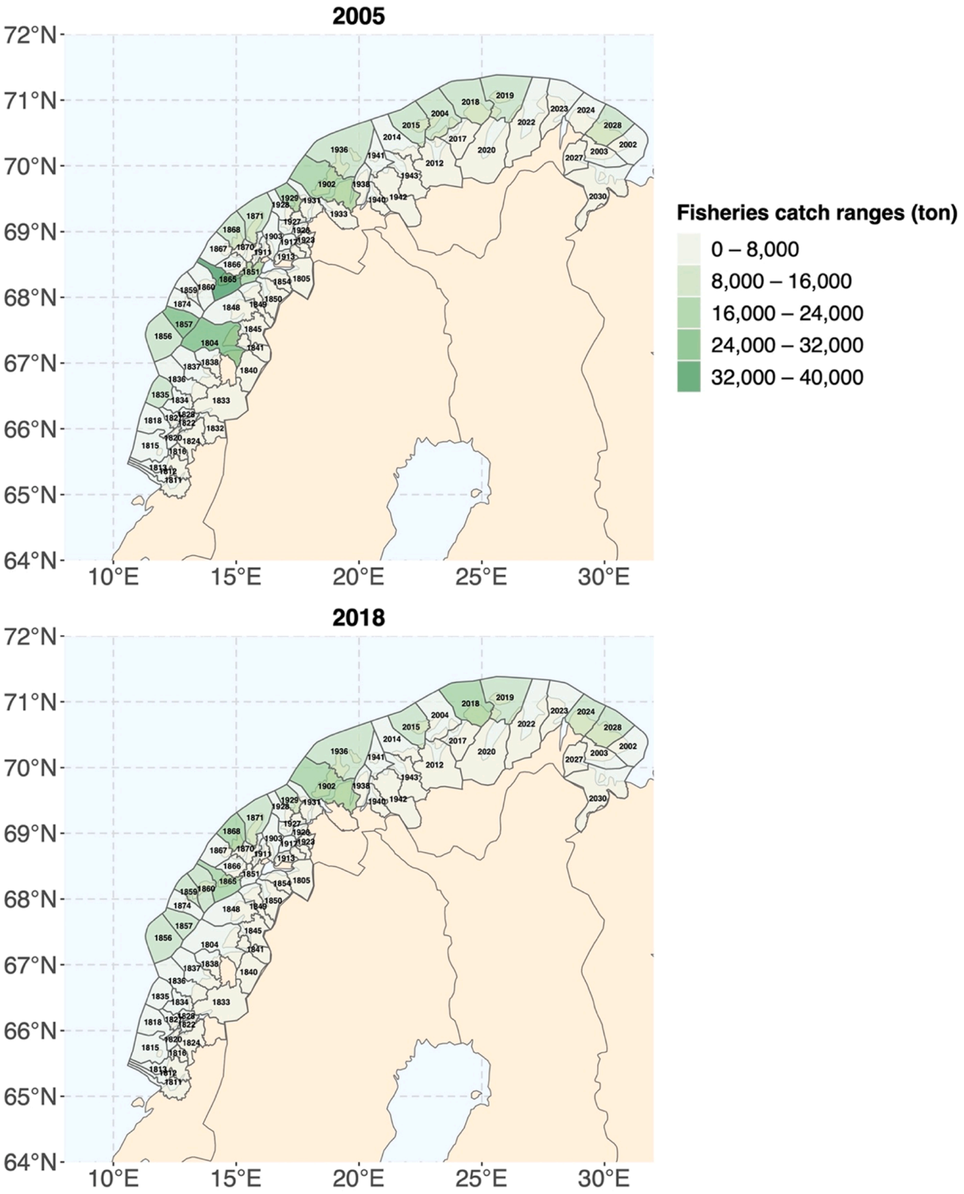

Fig. 2. Total fisheries landings of Atlantic cod, Atlantic herring, Atlantic mackerel, capelin, haddock, king crab, saithe, and deep-water shrimps, in Northern Norway in 2005 (above) and 2018 (below). Municipality numbers are plotted over the municipality polygons.

The posterior means and the 95% highest posterior density (HPD) intervals of the selected model parameters and hyperparameters for fisheries and aquaculture are presented in the Table 4. This interval is preferred over 95% equal tail posterior interval, because it contains most credible posterior values of the parameter, even if the parameter's posterior distribution is non-symmetrical.

Of all the included covariates, only sea area appeared to be important for fisheries production (did not include zero in the 95% HPD interval). Sea area's slope was positive (5.379) (Table 4), showing that a larger coastal area (by 1 standard deviation) was associated with about 5-thousand-ton increase in the fisheries production, on average for all study municipalities. Overall temporal trend for fisheries was very small, and likely not different from zero given the estimated HPD interval (Table 4).

For aquaculture production, none of the included covariates were important (Table 5). However, we identified a global positive temporal trend in aquaculture production, with the mean estimate of a global trend of 1.082 (Table 4; Fig. 4). This temporal trend indicated about 8% increase in the total production over the study period.

The differential temporal trends for fisheries and aquaculture of each municipality are presented in Fig. 5. Among all the municipalities, the posterior distribution of differential trends did not include zero for only 2 municipalities: Øksnes (1868) and Bodø (1804), both located in Nordland County (Fig. 5). In Øksnes, a municipality of the Lofoten archipelago, the landings increased in 2018 (20 thousand tons) compared to 2005 (about 9 thousand tons), therefore the municipality's own temporal change was "significantly" different from the variation in fisheries landings in the whole Northern Norway (no temporal trend). On the other hand, Bodø had a negative differential trend following the decrease in landings from 2005 (25 thousand tons) to 2018 (1.6 thousand tons).

For aquaculture, the largest negative differential trend, thus, a negative deviation from the positive global trend, was observed in three municipalities: Sømna (1812) in southern Nordland, Flakstad (1859) and Vågan (1865) in the Lofoten archipelago. The steepest positive trend, giving the largest increase in aquaculture yield was observed in Bodø in Nordland, and Masøy (2018), Hasvik (2015) and Lebesy (2022)

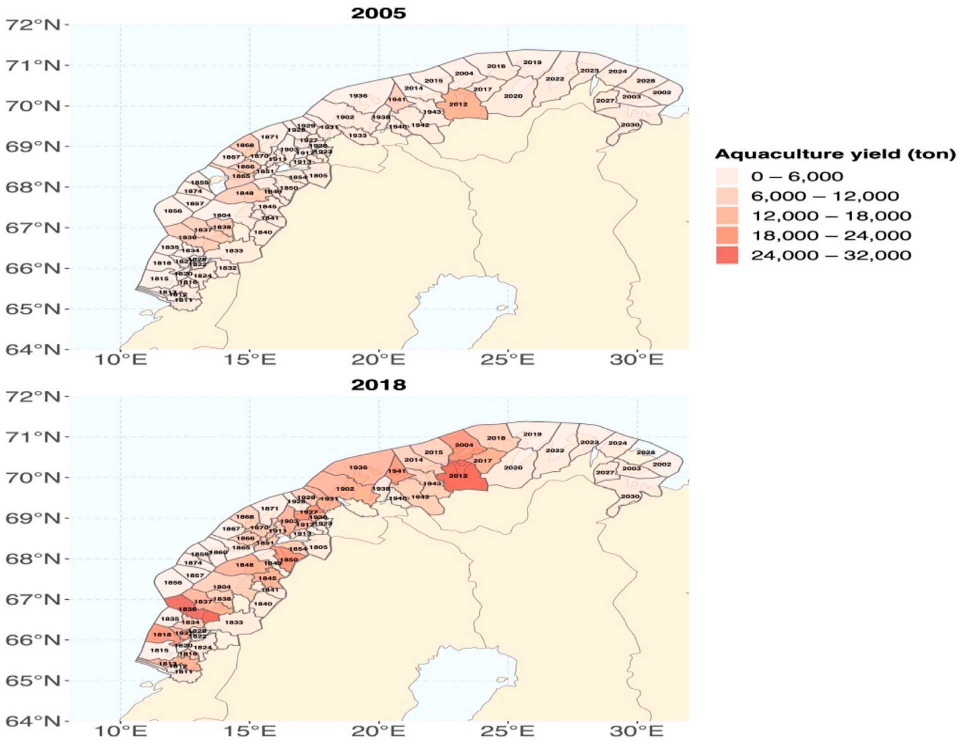

Fig. 3. Aquaculture annual yield of Atlantic salmon and rainbow trout in Northern Norway in 2005 (above) and 2018 (below). Municipality numbers are plotted over the municipality polygons.

Table 2

Deviance information criteria (DIC) of the considered Bayesian hierarchical models for fisheries production data.

Model type	DIC
Spatial random-effects model	30
Spatial-temporal model: no interaction, with temporal RW2 and random temporal effect	33
Spatial-temporal model: no interaction, with temporal RW2	29
Spatial-temporal model: no interaction, with linear temporal trend	30
Spatial-temporal interaction type I	32
Berardinelli model	17

Table 3

Deviance information criteria (DIC) of the considered Bayesian hierarchical models for aquaculture production data.

Model type	DIC
Spatial random-effects model	4377
Spatial-temporal model: no interaction, with temporal RW2 and random temporal effect	4214
Spatial-temporal model: no interaction, with temporal RW2	4206
Spatial-temporal model: no interaction, with linear temporal trend	4214
Spatial-temporal interaction type I	4203
Berardinelli model	4085

in Finnmark (Fig. 5). Interestingly, most of the municipalities of the Lofoten archipelago had deviated negatively from the positive general trend, pointing to no growth or decrease in aquaculture production. In Vågan for instance, aquaculture production decreased from 8 thousand tons in 2005 to only 424 tons in 2018, which explains a large negative deviation from the global trend. In contrast, the largest increase in farmed fish production occurred in southern Finnmark, which was reflected in a positive differential trend (Fig. 5) and absolute production values in 2005 and 2018 (Fig. 3). Alta (2012) was the largest farmed fish producer in Finnmark (Fig. 3), however, it did not feature large positive differential trend, because production in Alta was stably large throughout the study period.

When examining the spatial random effects (Table 5), we observed that the mixing parameter ϕ was equal to 0.075 in fisheries model, which means that the fraction of the marginal variance attributed to spatially correlated random effect u_i was relatively small (the closer ϕ to 0, the smaller the effect of u_i). In other words, the stochastic spatial component v_i had a much larger contribution to total spatial variation than u_i. This is an interesting result that can also be interpreted as a relative lack of spatial similarity in fisheries landings between the neighboring municipalities in our study, or that the adjacent municipalities did not necessarily have similar fisheries landings.

In the aquaculture model, the parameter ϕ was larger (0.302). This larger ϕ showed that spatial dependency was stronger for aquaculture production, or that larger similarities in aquaculture production were found between some of the adjacent municipalities. However, also for aquaculture, the unstructured spatial variability explained most of the spatial differences in the production.

Looking further into the spatial random effects, we can observe that there were considerably large spatial differences between the municipalities in terms of fisheries and aquaculture production (Fig. 6). As suggested by the Bayesian model for fisheries, the spatial random effect for an individual municipality varied from about -3.5 and 3.9 (exponentiated means were 0.045 and 51.7, respectively). These effects translated into at most 95% lower fisheries landings in a municipality with the most negative spatial random effect, to 52 times larger fisheries landings in a municipality with the largest positive spatial random effect, compared to the average landings in the region. Among the municipalities with the largest positive spatial deviation in the fisheries production were municipalities located in the Lofoten archipelago, particularly, Lødingen (1851), Vågan (1865) in the southern Nordland County and Berg (1929) in Troms. The largest negative spatial difference in fisheries landings was observed for municipalities Vega (1815) in southern Nordland and Karlsøy (1936) in Troms (Fig. 6). The result that Karlsøy municipality had the strongest spatial negative deviation, while Lødingen had the largest positive, may seem confusing given that these

Table 4
Posterior means and 95% highest posterior density (HPD) intervals for fixed effects and hyperparameters of the Bayesian hierarchical model for fisheries and aquaculture production data.

Parameter type	Parameter	Posterior mean	95% HPD interval	Exponentiated mean
Fixed effects for fisheries model	Intercept	-0.518	(−0.951, −0.088)	0.610
	Sea area	1.661	(1.249, 2.071)	5.379
	Percent in the workforce	0.010	(−0.113, 0.133)	1.012
	Distance North to South	0.476	(−0.210, 1.160)	1.711
	Population growth	0.079	(−0.036, 0.193)	1.084
	Aquaculture production	-0.033	(−0.154, 0.088)	0.969
	Year (temporal trend)	-0.019	(−0.041, 0.003)	0.981
Fixed effects for aquaculture model	Intercept	0.087	(−0.321,0.493)	1.114
	Sea area	-0.139	(−0.578, 0.298)	0.892
	Percent in the workforce	0.034	(−0.057, 0.125)	1.036
	Distance North to South	-0.333	(−1.461, 0.792)	0.846
	Population growth	0.051	(−0.039, 0.130)	1.053
	Fisheries production	-0.060	(−0.187, 0.067)	0.944
	Year (temporal trend)	0.079	(0.065, 0.093)	1.082

Table 5
Posterior means and 95% highest posterior density (HPD) intervals for hyperparameters of the Bayesian hierarchical model for fisheries and aquaculture production data.

Parameter type	Parameter	Posterior mean	95% HPD interval
Hyperparameters for fisheries model	Mixing parameter ϕ	0.075	(0.017, 0.158)
	Precision of the spatial random effect	0.343	(0.200, 0.498)
	Precision of the spatial-temporal interaction δ_i	606.055	(108.278, 1368.699)
Hyperparameters for aquaculture model	Mixing parameter ϕ	0.302	(0.059, 0.606)
	Precision of the spatial random effect	0.255	(0.135, 0.385)
	Precision of the spatial-temporal interaction δ_i	229.947	(102.961, 352.893)

municipalities were not producing respectively, lowest and largest amount of wild capture fish (Fig. 2). However, the sea area was an important covariate for fisheries production, hence, Karlsøy with the largest sea area among the municipalities in the study (nearly 4800 km^2), had unproportionally low fisheries landings. On the contrary, Lødingen has a sea area almost 10 times smaller (516 km^2) than Karlsøy but had comparatively large landings (about 32 thousand tons in 2005).

Spatial random variation of aquaculture production revealed that the smallest and the largest spatial random effects were, respectively, − 4.5 and 2.5 (exponentiated means were 0.031 and 17.1, respectively). In other words, spatial random effect implied at most 97% lower production in a municipality with the most negative spatial random effect, but 17 times higher production in a municipality with the largest positive random effect, compared to the regional average. The municipalities with the largest positive spatial random effects were Steigen (1848) and Vågan (1865) in Nordland, Karlsøy (1936) in Troms, Alta (2012), Hammerfest (2004), and Loppa (2014) in Finnmark. The largest negative spatial deviation from the average production was observed in the 9 municipalities: Hemnes (1832), Røst (1856), Værøy (1857), Andøy (1871) in Nordland county; Balsfjord (1933) in Troms; Porsanger (2020), Berlevåg (2024), Vardø (2002) and Vadsø (2003) in Finnmark. For these municipalities, the deviation from the overall regional production was negative only due to zero production in these municipalities in 2005–2018 or most of the study years. The municipalities were still included in the analysis because they had fisheries production (recorded landings), and for better comparability of the fisheries and aquaculture models we used the same list of municipalities in both sets of models.

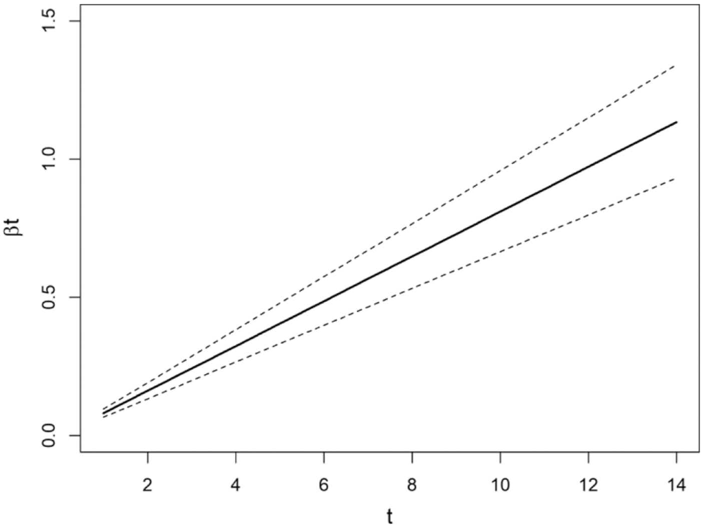

Fig. 4. General temporal trend βt (posterior mean) in aquaculture production in Northern Norway estimated by the Berardinelli model. t denotes years from 2005 to 2018 (14 years). The temporal trend is presented on an exponential scale. For the details on trend estimation, see the Methods section.

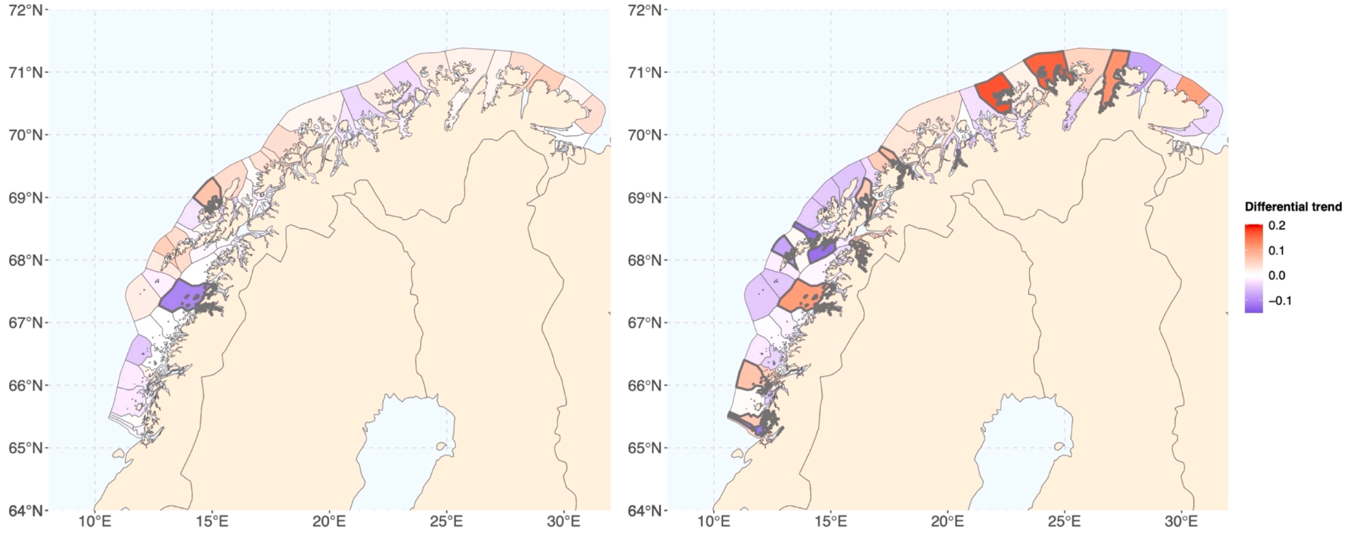

Fig. 5. Differential temporal trends δ_i (posterior means) in fisheries landings (left) and aquaculture production (right) in Northern Norway, estimated by the Berardinelli model. Municipalities with thick borders had differential temporal trend most likely differed from zero (important trend). For the details on differential trend estimation, see the Method section.

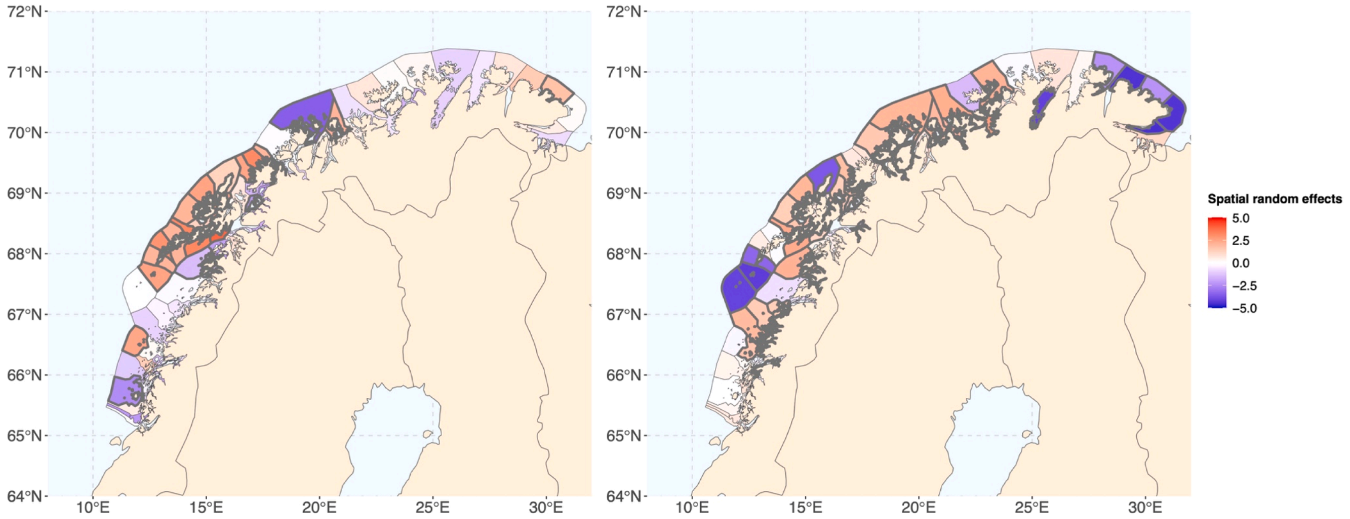

Fig. 6. Spatial random effects (posterior means) for fisheries landings (left) and aquaculture production (right) in Northern Norway. Municipalities with thick borders had random effects most likely differed from zero (important effects).

The other municipalities with negative spatial random effect were those where aquaculture production was small or zero in some of the study years, such as Moskenes (1874), Leirfjord (1822), Gamvik (2023), Båtsfjord (2028).

5. Discussion

5.1. Covariates' effects on seafood production

In this study, we aimed to investigate variability and co-development of fisheries and aquaculture in Northern Norway in 2005–2018. The effects of the two industries on each other were not detected, but the analysis revealed wide spatial variability in municipalities' seafood production, and an increasing production trend in aquaculture. Of the included covariates (sea area, percent of people in the workforce, distance from South to North, population growth, production of the second seafood industry), sea area was important for fisheries landings, while demographic and economic characteristics of a municipality did not seem to influence the production levels of either industry. Similarly, the location along the South-North direction had no effect on seafood production, suggesting that geographical gradient alone could not explain the variation in the coastal fisheries or aquaculture production levels.

Sea area effect on fisheries landings (Table 4) suggested that in general, municipalities with larger sea areas had higher rates of fish landings. We believe, however, that in addition to reflecting large fishing areas close to a municipality, sea area may have bespoken municipality's size and the number of operating harbors, as well as the presence of other convenient infrastructure (airport, hotels, fisheries organizations centers and maintenance plants). As a result, wide possibilities for fish sale and transport, together with the access to other infrastructure in lager municipalities, were likely translated into a higher number of landings in municipalities with larger sea areas.

However, the association between larger sea area and more landings was not uniform across all studied municipalities, and at least two exceptions can be detected. Karlsøy municipality (1936) in Troms, for instance, has one of the largest sea areas (around 4800 km^2), but landings were not the highest there. On the other hand, Lødingen municipality (1851) in Lofoten has nearly 10 times smaller sea area than

Karlsøy (516 km2) but had relatively high landings delivered throughout the studied period (Fig. 2). This result was also reflected in the spatial random effects of fisheries catches: Karlsøy had a large negative spatial random effect compared to large positive random effect of Lødingen. In other words, these two municipalities were respectively, negative and positive deviates from the average fisheries catches in Northern Norway, given their sea areas. Such deviations suggest that in some cases, fish caught in waters of a municipality with large sea area (e.g., Karlsøy) were delivered in a municipality with a smaller sea area but a with wider choice of fisheries-related infrastructure (e.g., Tromsø).

5.2. *Spatial and temporal variation in fisheries and aquaculture*

Temporal variation was markedly different for coastal fisheries and aquaculture. The lack of temporal changes in fisheries landings, except for the two municipalities, showed that there were no major events that might have impacted coastal fisheries in Norway since 2005, and fish stocks included in the study were generally well managed. However, if we would have included longer time series, for example, since 1990 s, we would have noticed fluctuations. For aquaculture, however, a growing annual yield reflected the rapid development of this industry in Northern Norway during the study period (Statistics Norway). In addition, a positive trend in aquaculture production agreed with the Norwegian national plan to further expand fish farming, by increasing production level 5 times by 2050 (White paper 22, 2012–2013).

Spatial variation, on the other hand, was substantial for both seafood industries. Based on the spatial variation of fisheries and aquaculture we can infer that for both industries, spatial correlation with adjacent municipalities played only a minor role (but was not absent). In the Lofoten region (Fig. 5), similarity of spatial random effect for fisheries was noticeable, but not as much for the other municipalities. For the aquaculture, spatial similarity was stronger (larger mixing parameter, Table 5), indicating regional trends beyond the scale of municipalities. In fact, the aquaculture production of a single company, especially, of the largest producers in the region, is usually spread across municipalities' borders. The company might have several production locations build in the adjacent municipalities, and the total amount of fish under production can be redistributed between the locations as needed, for example, when one of the locations must undergo fallowing or when the number of fish exceeds the location's capacity. We therefore assume that fish transport between the locations, and other benefits of building regional clusters of production facilities, may partly explain slightly larger spatial similarity between the municipalities' aquaculture yield compared to fisheries landings.

The stochastic spatial variation was however more important for both industries, which can be interpreted as a lack of spatial dependency in most areas of the Northern Norway. From a non-technical point of view, strong stochastic spatial variation showed that municipalities with largest or smallest seafood production were not necessarily surrounded by municipalities with as high or as low levels of production. In addition, this stochastic temporal variation reflects an additional, spatially driven covariate that was not captured in our data. Since distance from South to North was not an important covariate, extra spatial variation is unlikely to be related to geographical location in the South or in the North. More plausibly, this unexplained spatial variation was related to other factors that influenced the presence and production rates of seafood in Northern Norway. The possible additional factors are further discussed below.

5.3. *Additional factors affecting seafood production but not measured in the study*

The most natural explanation for a stochastic spatial variation in fisheries is the access to fisheries resources, for instance, the cod and capelin stocks of the Barents Sea, which would determine where the main fisheries centers are located. However, following structural changes in the quota system after 1980 s, fisheries became more centralized in the most convenient landing locations with a sufficient infrastructure.

Among the infrastructure-related factors, a decisive one was most likely the access to fisheries landings plants. A study by Cojocaru et al. [24] has shown that a municipality is likely to sustain its landings plants if it was in fisheries business for already a long time, and when there were multiple active landing plants in a municipality. In other words, traditional, long-established fisheries centers were likely to remain in fisheries, also under the quota reorganization crisis and beyond. In our study, typical examples of such traditional fisheries centers are the Lofoten archipelago, Skjervøy, and Karlsøy municipalities, and the Northern Finnmark municipalities. Accordingly, all these municipalities had a large positive spatial deviation from the average fisheries landings (Fig. 6).

Thus, for fisheries landings, spatial variation had a lucid explanation based on tradition, access to resources, and infrastructure. For aquaculture however, there must be additional factors that defined the spatial dissimilarity in production. The access to resources is usually not a limiting factor for aquaculture, and tradition is unlikely to play an important role for this rapidly developing industry, whereas the availability of suitable coastal areas (for salmon growth) is essential. Norwegian coast features multitude of fjords that are potentially optimal for fish farming, nevertheless, only some municipalities with such fjords succeeded as farmed fish producers. We have seen that among the aquaculture leaders in Northern Norway are municipalities Alta, Skjervøy, and Hammerfest (Fig. 3). A comparatively high production of farmed fish in Finnmark during the study period (2005–2018) can be explained by the lower remuneration requested from applications in these regions (in 2003 and in 2009), and by prioritization of these regions in the license acceptance in 2013 [32]. Therefore, license allocation process could have promoted earlier establishment and faster growth of fish farming in these municipalities.

In addition to license allocation priorities, aquaculture growth and opening of new farms were limited by environmental concerns, such as salmon lice and farmed fish escapes. Both lice disease and escaped fish are harmful for wild salmonid populations, and it was recognized by researchers and practitioners as one of the crucial factors impeding aquaculture growth in Nordic countries and Canada [90]. In Norway, the debates on lice problem initiated the introduction of the lice risk assessment procedure [91], based on which the new farms can be opened or existing farms can increase production. Although this problem does not affect Northern Norway to the same extent as Central and Western Norway [91–93], municipalities may still oppose to the opening of new farms, being aware of the environmental aspects of aquaculture [94].

Opposition by municipalities to the establishment of aquaculture sites can also stem from reportedly limited economic benefits to the municipal population offered by aquaculture industry. Although at the onset of its history in Norway, aquaculture was seen as a solution to unemployment and economic struggles of remote municipalities, over time the industry transformed from family-owned businesses to large companies, some of which had little interest in the local economy [95, 96]. Locations of production sites and administration were therefore chosen not where there was a highest demand for employment, but where it was most convenient for fish farmers. In addition, the already operating companies were paying taxes to the Norwegian government, not to a municipality of production, so economic benefits for a municipality were obscure. This lack of evident benefits of aquaculture industry to a municipality leaded to multiple oppositions to renting coastal space for new farming locations. In turn, the municipal resistance and centralization of fish farming contributed to the geographical imbalance in fish farming yield across Northern Norway.

Another factor that hinders aquaculture growth in Norway and Nordic countries alike is the overlap with essential fisheries areas or less commonly, with esthetic touristic locations [90]. Spatial conflicts between fisheries and aquaculture used to be only seldom in Northern

Norway compared to Central and Western Norway but were predicted to escalate in the near future [97]. Although we do not have a complete overview of such conflicts, we are aware that they have occurred on a small-scale in Northern Norway and involved, for instance, overlap between aquaculture and important fishing areas for shrimp or dwelling areas of other marine species [94,98,99].

Although answering the question on which factors boost and which suppress fisheries or aquaculture production in Northern Norway is difficult based on our statistical models, the absence of municipality's population and unemployment effects in addition to the large spatial variation can provide some insights. We believe that the combination of factors that determines success in either industry is rooted in the history of a municipality and path dependency of the seafood production [100,101]. We conjecture that the fisheries paths rest on the proximity to fishing grounds combined with the local fishing traditions and concurrent national fisheries regulations, while the aquaculture paths are determined by the access to suitable coastal spaces, but also by the presence of sufficient capital and supportive licence allocation policies. In addition, the casual interactions between these specific factors can be conducive to a municipality's successful seafood venture, but discerning such interactions by statistical models is problematic.

5.4. *The mutual effects of the fisheries and aquaculture*

Our study demonstrated no effect of aquaculture on fisheries and vice versa, refuting our hypothesis that the two seafood industries influence each other's growth. The lack of mutual effects of the two industries in our study may show that in the studied period (2005–2018), conflicts for coastal areas in Northern Norway were not pronounced, with some municipalities specializing mainly on fish farming when fisheries declined [98], while others—mainly on fisheries (the Lofoten archipelago). Besides, no observed effect of aquaculture on fisheries may denote that the aquaculture management in 2005–2018 successfully considered potential impacts on the coastal fisheries through prudent coastal zone planning and mapping of principal fishing or fish spawning areas [102]. Therefore, we would cautiously suggest that the current seafood policy in Northern Norway allows the two industries to co-exist without persistent trade-offs. We however cannot exclude that disputes between the two industries will become more common as aquaculture sites occupy larger areas or their number within municipalities increase.

On the other hand, interactions between fisheries and aquaculture can occur through processes not related to spatial conflicts, for example, through seafood market prices and demand for wild fish for fishmeal production [103]. But we believe that such effects cannot be identified by the small-scale analysis of the present study. Moreover, as suggested by the recent study [104], the impact of a growing aquaculture on fisheries landings was only observed in the countries where aquaculture is a dominating seafood sector, which is not the case for Norway.

5.5. *Limitations of the study*

There are several limitations in our study, and here we discuss how we alleviated them (where possible) and to what extent they may have affected our analyses. First, fisheries landings in Norway are registered at the location where fish were landed and sold, and in addition to detailed information of the catch, the records include technical details about the fishing vessel and the vessel's home port. In the present study, we ignored the information on the vessel's home municipality and used all the landings delivered to a municipality as the response variable. However, larger vessels tend to fish across several municipalities but deliver fish in a single preferred municipality. Retrieving fishing locations for each species and regions along Northern Norwegian coast would require a comprehensive analysis of yet insufficient data; therefore, we did not attempt to calculate landings originating from specific locations along the coast. Relying on landings per municipality data, however, implied that in some cases, the fish delivered in a municipality was caught in the waters of another municipality. Such cases are not uncommon, but to mitigate this weakness we limited landings data to fleet size of 28 m and below (coastal fleet in the Norwegian definition). Therefore, in the interpretation of the data analyses it is important to keep in mind that fish landed in a municipality is not always equal to fish resources of this municipality's waters. In such instances, our analysis could only reflect to which extent a particular municipality was a preferred fish landing location, given the presence of aquaculture, and the role of socio-economic or other relevant factors.

Finally, we would like to mention limitations related to Bayesian mixed model approach that we applied in this study. Although Bayesian approach can accommodate models with complex correlation structures, spatial-temporal models for continuous data with zeroes are still under development. One of such methods—Bayesian spatial-temporal models based on Tweedie distribution, was applied in this study. Models using Tweedie distribution are more common for geo-referenced type of data such as fish catches locations [82,84], while we might be among the few who used this distribution for irregular lattice data (municipalities). We also remind that we resorted to weakly informative priors for fixed effects in our study (for intercept and effects of covariates). Using weakly informative priors is a typical approach when prior information on the effect is scant or unreliable, as was the case in our study. However, we hope our work will serve as an example and a possible source of prior information for later studies that will capitalize on the flexibility of a Bayesian framework for seafood production analyses, also beyond Norway.

5.6. *Concluding remarks*

Our study is among the first that analyzed the Northern Norwegian fisheries and aquaculture as a seafood production alliance on a municipality level. Based on our data, the statistical analyses did not identify important factors for aquaculture production in Northern Norway and did not confirm the reciprocal effects of aquaculture and fisheries. We therefore assume that the main drivers of both industries could not be detected among the applied covariates, because the prosperity of seafood industry in Northern Norway is determined by a complex interplay of geographical, political, economic, and environmental factors. The absence of reciprocal effects of fisheries and aquaculture, in our view, signify that under the present policies and seafood production levels in Northern Norway, trade-offs between the two industries are uncommon, but may become recurrent in the future.

Employing a flexible Bayesian approach, however, allowed us to uncover a strong spatial variability in both seafood industries in Northern Norway, and a temporal change in the aquaculture production. Furthermore, using the mixed Bayesian model we were able to fully account for the between-municipalities variability, avoiding misinterpretation of covariates' effects when such effects are confounded by the differences between the municipalities.

Based on our analyses, we propose that future studies interested in the development of fisheries in Norway consider longer time series and possibly, compare cases from Northern Norway to those in Central and Western Norway. Geographical comparison of fisheries on a country scale may reveal original associations that we were not able to demonstrate for Northern Norway only. For aquaculture, future studies may consider aggregating municipalities or using aquaculture production areas as a study unit [105], since full production cycle often occurs across the municipalities' borders.

CRediT authorship contribution statement

Marina Espinasse: Conceptualization, Data curation, Methodology, Software, Formal analysis, Visualization, Writing – original draft. **Eirik Mikkelsen**: Supervision, Conceptualization, Writing – review & editing of the manuscript. **Sigrunn Holbek Sørbye**: Software, Formal analysis, Writing – review & editing of the manuscript. **Mette Skern-Mauritzen**:

Funding acquisition, Writing – review & editing of the manuscript. **Jannike Falk-Andersson**: Conceptualization, Writing – review & editing of the manuscript. **Per Fauchald**: Funding acquisition, Project administration, Supervision, Conceptualization, Writing – review & editing of the manuscript.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that would have influenced the literature and work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

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